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ABSTRACT. Although the long-studied conditions of a plasma jet across a uniform magnetic field are simple and predictable, in a nonuniform case the behavior differs from the theoretical. Various examples are given. Experimental observations show that the plasma jet in a gradient field in no way contradicts conclusions in the elementary theory of plasma drift.

The motion of a plasma jet across a uniform magnetic field is one of the simplest phenomena of plasma physics, studies long ago by Alfven (ref. 1). /825*

Assuming that the lateral dimensions of the plasma are $l > \frac{v\omega_c}{\omega_\rho^2}$ where v is the speed of the plasma, and ω_c and ω_ρ are the cyclotron and plasmic frequencies of the plasma corpuscles, the polarization forces of the quasineutral plasma exceed the Lorentz force, and the plasma jet as a whole must move across the magnetic field. If the temperature of the two plasma components is low in comparison with the kinetic energy of the plasma motion, the magnetic field in the plasma jet will be close to a vacuum. From the point of view of the laboratory coordinate system, the plasma becomes polarized as it moves across the field, and electric field $E = v_x B/c$ emerges. The thickness of the volume charge strata produced by the polarization is of the order of magnitude $\delta \approx \frac{1}{\omega_c + \omega_\rho}$.

However, numerous experimental investigations (refs. 2 and 3) have revealed that the behavior of the plasma jet in certain cases differs a great deal from the theoretical behavior. At a density of $n < 10^{13}\,cm^{-3}$ (ref. 2), for example, the plasma moving across a magnetic field changes its direction, because of the electrostatic forces in the polarization layers, and begins to move along the lines of force and in the opposite direction of the magnetic field. At higher density levels (ref. 4) it no longer flows along the field, but the speed of its forward motion diminishes with the increasing magnetic field B, and $u \approx a + b/B$.

Alfven (ref. 1) and Karlson (ref. 5) made a theoretical study of the motion of unlimited space plasma in a dipole-type nonuniform field (ref. 5) and in a cylindrically symmetrical field whose gradient coincides with the radius (ref. 6).

* Numbers in the margin indicate original pagination in the foreign text.

However, comparison (ref. 6) with the experimental results is impossible inasmuch as the calculationsare based on the assumption of the unlimitedness of a diametrical dimensions of the plasma jets.

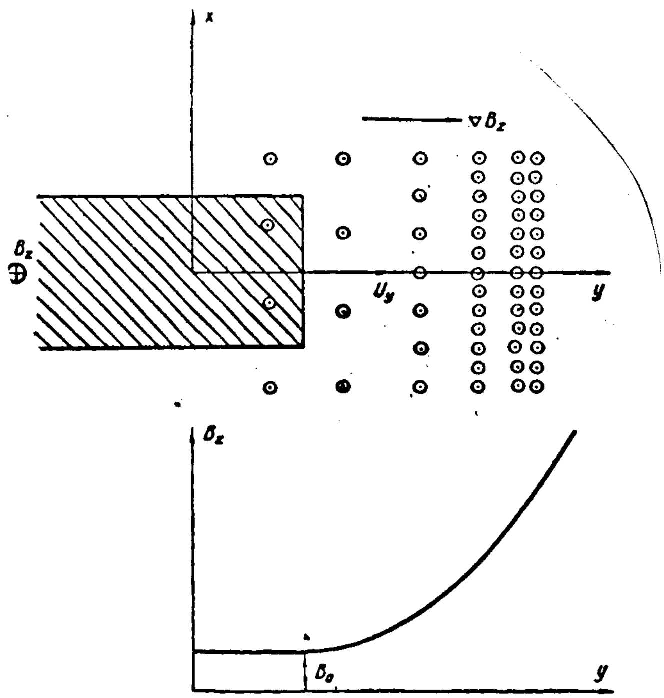
This study shows that, according to experimental observations, the behavior of a plasma jet in a gradient field does not in any way contradict the conclusions in the elementary theory of plasma drift.

Let a limited plasma coagulate first move in uniform field B_0 at constant velocity u_0. It is assumed that the motion is adiabatic and $\mu_i = \frac{nkT}{B_0}$ considerably exceed $\mu_e = \frac{nkT}{B_0}$. Having passed the uniform part of field B_0, the plasma clot finds itself in a gradient field (see figure), and we assume that ∇B is parallel to u_y. The interaction between the magnetic moment of the plasma and the gradient field results in a drift in the x direction

$$\vec{u}_{x_1} = -\frac{c}{qB^2}[\mu\vec{\nabla}B \times \vec{B}] = -\frac{\mu c}{qB}\nabla B \tag{1}$$

and an inertia drift (ref. 8)

$$\dot{u}_{x_2} = -\frac{c}{qB^2}\left(M\frac{du_y}{dt}\times B\right) = -\frac{Mc^2}{qB}\frac{d}{dt}\left[\frac{E_x}{B}\right] = \frac{Mc^2}{qB}\left[\frac{1}{B}\frac{dE_x}{dt} - \frac{E_x}{B^2}\frac{dB}{dt}\right]. \tag{2}$$



Assuming that $u_x = u_{x_1} + u_{x_2}$ and making use of the Poisson equation

$$\frac{dE}{dt} = 4\pi q n u_x, \tag{3}$$

we obtain

$$u_x = -\frac{\mu c}{qB}\nabla B - \frac{\mu c^2}{qB^2} 4\pi q u_x + \frac{Mc^2}{qB^2}\left(\frac{E_x}{B}\right)\nabla B u_y$$

and

$$u_x = -\frac{\mu c}{\varepsilon q B}\nabla B + \frac{Mc}{\varepsilon q B}\frac{\nabla B}{B} u_y^2. \tag{4}$$

After a substitution in (3), we obtain

$$\frac{dE_x}{dt} = \frac{4\pi n M c^2}{\varepsilon B}\left(-\frac{\mu}{M} + \frac{u_y^2}{B}\right)\nabla B, \tag{5}$$

where

$$\varepsilon = 1 + \frac{4\pi n M c^2}{B^2}.$$

The forward speed u_y changes with the changing polarization field E_x:

$$\frac{du_y}{dt} = c\frac{d}{dt}\left(\frac{E}{B}\right) = \frac{4\pi n M c^2}{\varepsilon B}\left(-\frac{\mu}{M} + \frac{u_y^2}{B}\right)\nabla B. -$$

$$-\frac{cE}{B^2}\nabla B u_y = \frac{\varepsilon - 1}{\varepsilon}\left(-\frac{\mu}{M} + \frac{u_y^2}{B}\right)\nabla B - \frac{u_y^2}{B}\nabla B = \frac{\varepsilon - 1}{\varepsilon}\frac{\mu}{M}\nabla B - \frac{u_y^2 \nabla B}{\varepsilon B}, \tag{6}$$

with $\varepsilon \gg 1$

$$\frac{du_y}{dt} = -\frac{\mu}{M}\nabla B - \frac{u_y^2 B \nabla B}{4\pi n M c} \tag{7}$$

or

$$\frac{du_y}{dt} = \frac{d}{dy}\left(\frac{u_y^2}{2}\right) = -\frac{\mu \nabla B}{M} - \frac{u_y^2 \nabla B^2}{8\pi n M c^2}.$$

In the cases under consideration ($n \sim 10^{14}\,\mathrm{cm}^{-3}$, $B \sim 10^{13}$ gauss, $T \sim 1$ eV), the first term on the right part of (7) is 10^6 times larger than the other. Therefore,

$$d(u_y^2) = -\frac{2\mu}{M}dB \quad \text{or} \quad u_y^2 = u_0^2 - \frac{2\mu}{M}(B - B_0).$$

All these conclusions cannot usually be considered as the real theory of a plasma jet moving across a magnetic field even in the case of plasma without a collision. These are the basic assumptions made in our calculations:

1) the plasma coagulate in primary field B_0 has a magnetic moment; 2) the field gradients and velocities are such that the law of adiabatic conditions for ions is fulfilled. In the above-cited example the Larmor radius is $\rho \sim 10^{-1}$cm, and therefore the field gradients cannot be very small. As for the first assumption, its feasibility depends largely on the method of plasma formation. If the plasma comes into being in a space where the magnetic field equals zero, and then moves in the direction of a gradient field, a magnetic moment develops after some oscillations (ref. 7).

In the case the magnetic moment of the plasma is too small and its density low, the second term of equation (7) may play a predominant role

$$\frac{d\,(u_y^2)}{u_y} = -\frac{1}{4\pi n M c^2}\,\nabla B^2 \qquad (9)$$

or

$$u_y^2 = u_0^2 \exp\left(-\frac{B^2 - B_0^2}{4\pi n M c}\right).$$

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